

N72-11431

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**EXPLORATORY STUDY OF FRICTION WELDS
IN UDIMET 700 AND TD-NICKEL BAR**

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1. Report No. NASA TM X-2411		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle EXPLORATORY STUDY OF FRICTION WELDS IN UDIMET 700 AND TD-NICKEL BAR				5. Report Date November 1971	
				6. Performing Organization Code	
7. Author(s) Thomas J. Moore				8. Performing Organization Report No. E-6425	
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135				10. Work Unit No. 114-03	
				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>Friction welded butt joints were made in both Udimet 700 and TD-Nickel bar. Also, dissimilar metal friction welds were made between these materials. Friction welding of Udimet 700 shows great promise because the welds were found to be as strong as the parent metal in stress rupture and tensile tests at 760° and 980° C. The weld line was not detectable metallographically in the heat treated condition. Friction welding for TD-Nickel, however, holds little if any promise. TD-Nickel friction weldments could support only 9 percent as much stress as the base metal for a 10-hour stress-rupture life at 1090° C. Dissimilar Udimet 700/TD-Nickel friction welds could sustain only 15 percent as much stress as the TD-Nickel parent metal for a 10-hour stress rupture life at 930° C.</p>					
17. Key Words (Suggested by Author(s)) Friction welding Udimet 700 Superalloys TD-Nickel			18. Distribution Statement Unclassified - unlimited		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		22. Price* \$3.00	
				21. No. of Pages 19	

EXPLORATORY STUDY OF FRICTION WELDS IN UDIMET 700 AND TD-NICKEL BAR

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SUMMARY

An exploratory study was conducted on the structure and properties of friction welds in Udimet 700 (U700) and TD-Nickel (TD-Ni) bar materials. Also included were dissimilar Udimet 700/TD-Nickel friction welds. Since friction welding is a solid-state deformation welding process, problems associated with fusion welding (involving melting) these materials could hopefully be avoided. Butt welds were prepared by friction welding 12.7-millimeter (1/2-in.) diameter U-700 bar and TD-Ni bar. Specimens for elevated temperature tensile and stress-rupture testing were machined after a post welding heat treatment.

Friction welding of Udimet 700 shows great potential because the welds were found to be as strong as the parent metal in stress-rupture and tensile tests at 760^o and 980^o C. In addition, the weld line was not detectable by metallographic examination after postheating. Friction welds in TD-Ni or between U-700 and TD-Ni were extremely weak at elevated temperatures. The TD-Ni friction welds could support only 9 percent as much stress as the base metal for 10-hour stress-rupture life at 1090^o C. The Udimet 700/TD-Ni weld could sustain only 15 percent as much stress as the TD-Ni parent metal for a 10-hour stress-rupture life at 930^o C. Thus, friction welding is not a suitable joining method for obtaining high strength TD-Ni on Udimet 700/TD-Ni weldments.

INTRODUCTION

Precipitation hardened (PH) and dispersion-strengthened nickel-base alloys are two families of materials that offer great promise individually, or in composite structures for high-temperature applications such as jet engine components. Unfortunately, problems associated with fusion welding have prevented the full utilization of these materials.

For PH Ni-base alloys that are to be considered weldable by the gas tungsten-arc process, Bridaviskii and Zemzin (ref. 1) recommend the following limits in weight per-

cent: 1.25 to 1.50 titanium and 0.6 to 0.7 aluminum. Udimet 700 which was nominally 3.5 weight percent titanium and 4.3 weight percent aluminum far exceed these limits. Thus, not surprisingly, Owczarski (ref. 2) points out that fusion welding of Udimet 700 is likely to produce heat-affected zone hot cracking. Prager and Shira (ref. 3) report that Udimet 700 is virtually unweldable by fusion welding techniques due to strain-age cracking.

Since melting destroys the thoria dispersion and the textured microstructure in TD-Ni only 40 to 50 percent joint efficiency in elevated temperature tensile tests is obtained (ref. 4). So, fusion welding processes are also unsuitable for welding TD-Ni where high strength weldments are required.

Because of the above problems, solid-state welding processes assume great importance for these materials. One of the newer solid-state deformation welding processes is friction welding. The objective of this program was to determine whether friction welds that match parent metal strength could be produced between Udimet 700 and TD-Ni materials.

The idea of welding by seizure caused by rubbing two surfaces together was first patented in Great Britain in the early 1940's (ref. 5). But no development work followed. Friction welding, as it is now known, was developed by A. I. Chudikov and patented in Russia in 1956 (ref. 6). Technical articles on friction welding are now becoming more abundant but published data on the elevated temperature properties of friction welds are quite scarce.

In friction welding, one part is rotated with respect to the other. The pieces are then brought into contact under pressure in order to produce frictional heat. The pressure normal to the joint produces a solid-state weld with local plastic deformation. It should be emphasized that the friction heating and the plastic deformation are confined to the immediate vicinity of the joint. Friction also provides an effective cleaning action to remove surface contamination which would prevent the formation of metallic bonds across the weld interface.

This exploratory study was designed to determine the structure and properties of friction welded butt joints in Udimet 700 and TD-Ni bar. Also, dissimilar metal friction welds between Udimet 700 and TD-Ni were included in the evaluation. The weldments were evaluated on the basis of stress-rupture and tensile strengths between 760° and 1090° C. The weldments also were subjected to metallographic examination in the as-welded and heat-treated conditions.

All the friction weldments evaluated in this study were prepared by the Inertia Welder Department of the Caterpillar Tractor Co., Peoria, Illinois.

MATERIALS AND WELDING PROCEDURE

Materials

The parent materials were in the form of 12.7-millimeter (1/2-in.) diameter bar stock. The first was a wrought PH Ni-base alloy, U-700, in the form of commercially produced hot-rolled bar. Udimet 700, which is strengthened primarily by a gamma prime coherent precipitate (Ni_3Al , Ti), is useful between 750° and 1000° C. Listed in the following table is the mill analysis of the Udimet 700 material (heat number 6-3213) that was used in this study:

Composition, wt. %									
C	Cr	Ni	Co	Fe	Mo	Ti	Al	B	S
0.06	15.2	bal.	19.0	0.13	4.95	3.43	4.40	0.030	0.003

The other parent material, commercial TD-Ni (2 vol. % thoria in unalloyed nickel), was purchased from E. I. duPont deNemours and Company. The TD-Ni bar (12.7 mm, 1/2 in.) was in the wrought condition, and it contained very small and highly elongated pencil-shaped grains. TD-Ni has good stress-rupture strength and a stable microstructure at high temperatures. It is particularly useful at service temperatures between 1000° and 1200° C in moderate oxidizing environments. The strong textured structure in TD-Ni is produced by thermomechanical processing.

Welding Procedure

In butt welding bar, the axes of the two pieces to be welded are alined in the friction welding machine. One bar is fixed and the other is rotated around their common axis. In this respect, the friction welding machine resembles a lathe. The stored-kinetic-energy-friction (inertia) welding process that was used in this study was developed in the United States in the 1960's (ref. 7). This method utilizes the discharge of kinetic energy from a flywheel (rather than spindle drive) to rotate the moving part. In stored-kinetic-energy-friction welding, the flywheel, chuck, and one part are accelerated to a preset speed. The rotating part then is forced against the fixed part. As the flywheel slows down, it discharges almost all of its energy into the interface. The weld is complete when the rotation stops. The welding parameters used in this study are presented in table I. A decrease in length of about 3.8 millimeters (0.15 in.) was obtained for the

TABLE I. - FRICTION WELDING PARAMETERS FOR BUTT WELDS IN 12.7-MILLIMETER
(1/2-IN.) DIAMETER BAR MATERIALS

Material combination	Moment of inertia of flywheel		Flywheel speed, rpm	Axial pressure		Decrease in length, Δl	
	N/m ²	lbf/ft ²		MN/m ²	ksi	mm	in.
Udimet 700/Udimet 700	240	5	3 600	283	41	3.8	0.15
Udimet 700/TD-Ni	240	5	$\left\{ \begin{array}{l} {}^a_{10\ 200} \\ {}^b_{3\ 000} \end{array} \right.$	$\left\{ \begin{array}{l} {}^a_{69} \\ {}^b_{242} \end{array} \right.$	$\left\{ \begin{array}{l} {}^a_{10} \\ {}^b_{35} \end{array} \right.$	1.8	.07
TD-Ni/TD-Ni	7.7	.16	12 000	138	20	1.8	.07

^aInitial.

^bFinal.

Udimet 700 weldments. For the TD-Ni and for the Udimet 700/TD-Ni weldments the decrease in length was about 1.8 millimeters (0.07 in.). The Udimet 700/TD-Ni welds were made using a two-step procedure: initially with high speed and low pressure and then lower speed and high pressure. Because of the limited study, the effect of various welding parameters on weld strength was not evaluated. Thus, the parameters used in this exploratory study were chosen arbitrarily.

EVALUATION PROCEDURE

Postheating

All the friction weldments were postheated before the machining of test specimens. The Udimet 700 and the dissimilar Udimet 700/TD-Ni weldments were heat treated as follows (conventional heat treatment for U-700):

- Step 1 - 1170⁰ C, 4 hours in argon, air cool
- Step 2 - 1080⁰ C, 4 hours in argon, air cool
- Step 3 - 850⁰ C, 24 hours in argon, air cool
- Step 4 - 760⁰ C, 16 hours in argon, air cool

For the TD-Ni weldments postheating was as follows: 1260⁰ C, 1 hour in hydrogen, furnace cool.

Test Specimens

Specimens for stress-rupture and tensile testing of butt joints were machined from the friction weldments. In all cases, the weld joint was within the reduced section. All but two specimens were of the button head type with a reduced section of 4.1 millimeters (0.162 in.) in diameter and gage lengths between 15 and 30 millimeters (0.6 and 1.2 in.) because the pieces available for welding were of various lengths. Specimens 10 and 11 (from Udimet 700 weldments) had threaded ends and a 6.3-millimeter (0.250-in.) diameter by 28-millimeter (1.1-in.) reduced section.

Testing Procedure

All tensile and stress-rupture tests of the butt welds were conducted in air. The tensile test specimens were held at temperature for 5 minutes before application of load. For all tensile tests a crosshead speed of 1.3 millimeter (0.05 in.) per minute was maintained.

For the U-700 weldments, tensile and stress-rupture tests were conducted at 760^o and 980^o C. This brackets the principal temperature range of usefulness for Udimet 700. The TD-Ni weldments were tested at a typical service temperature for the TD-Ni material, 1090^o C. Udimet 700/TD-Ni weldments were tested at 930^o C because both of the parent metals have about a 1000-hour rupture life at the same stress level (103 MN/m² (15 ksi)) at this temperature (ref. 8).

Metallography

Friction butt welds of each materials combination were sectioned for metallographic examination in the as-welded and heat-treated conditions. Diamond pyramid hardness (DPH) microhardness determinations also were made within selected areas of the weldments. A 500-gram load was used when making the hardness impressions. At least five hardness impressions were averaged for each reported value. In addition, fracture profiles were obtained from tested stress-rupture specimens of each materials combination.

RESULTS AND DISCUSSION

Udimet 700 Weldments

Deformation pattern. - Figure 1 illustrates the pattern and the extent of the plastic deformation in the Udimet 700 friction weldments. This flow pattern indicates that the

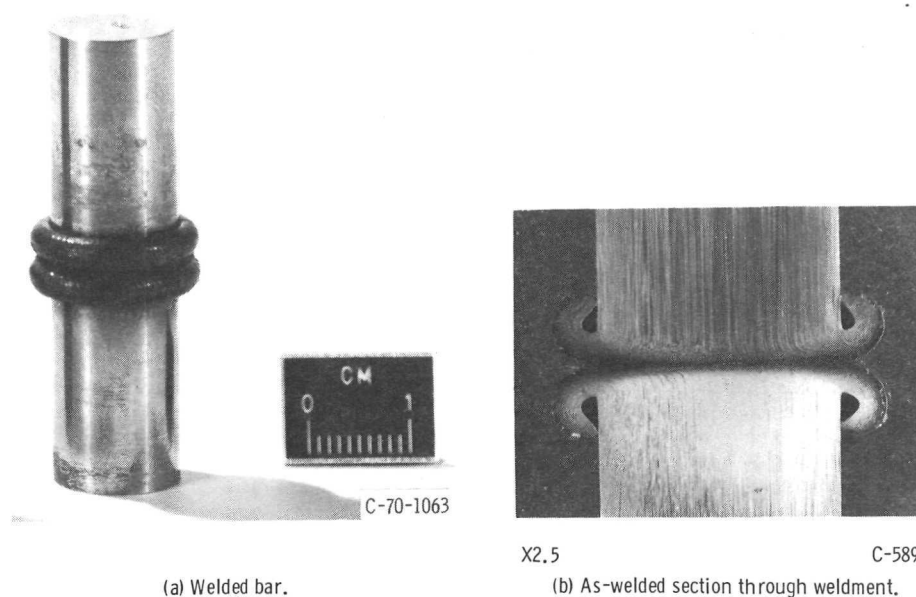


Figure 1. - Friction weld in Udimet 700 showing extent and pattern of plastic deformation that took place during welding.

TABLE II. - TENSILE PROPERTIES OF FRICTION WELDS

Specimen number	Test temperature, °C	Ultimate tensile strength		Elonga- tion, percent	Reduction in area, percent	Fracture location	Joint efficiency, ^a percent
		MN/m ²	ksi				
Udimet 700/Udimet 700							
3	760	935	135.5	14	33	Parent metal ↓	100 ↓
4	760	1025	148.9	15	26		
5	980	387	56.1	9	26		
6	980	474	68.6	7	24		
TD-Ni/TD-Ni							
4N	1090	41	5.9	(b)	11	At weld	30
Udimet 700/TD-Ni							
2-UN	930	76	11.0	(c)	(c)	Square edge,	42
3-UN	930	83	12.0	(c)	(c)	At weld	46

^a Joint efficiency = $\frac{\text{Weld strength}}{\text{Parent metal strength}} \times 100$.

^b Fractured surfaces could not be placed in contact to measure due to protrusions.

^c No measurable elongation or reduction in area.

proper combination of welding parameters (flywheel size, speed, and thrust) was used (ref. 7). Sufficient heating has taken place near the centerline of the bar, and the width of the heat-affected zone is slightly greater near the periphery. Finally, enough plastic deformation has been produced to remove impurities and foreign material from within the joint.

Mechanical properties. - Tensile properties shown in table II for duplicate tests conducted at 760^o and 980^o C show a 100-percent joint efficiency¹ for the Udimet 700 butt welds. For all four specimens (Nos. 3, 4, 5, and 6), fracture took place in the parent metal.

In stress-rupture tests at 760^o and 980^o C the butt welds were found to be equal in strength to the parent metal. The test data shown in table III are plotted in figure 2 along with the literature values (ref. 8) of the parent metal strength. For the 760^o C tests the shorter-time test specimen (No. 7) failed in the parent metal. The longer-time test specimen (No. 10), which ran for 460 hours, failed near the weld. Both specimens tested at 980^o C failed near the weld.

Metallography. - The as-welded microstructure in figure 3(a) shows a light-etching band at the weld plane. Also evident, next to the light band, are flow lines indicative of plastic deformation. DPH hardness (456), however, was uniform across the weldment. Figure 3(b) shows a recrystallized structure in which all evidence of the weld has been removed by the four-step heat treatment. The intragranular gamma-prime particles were not resolved under the light microscope. Except for at the surface where the pattern of plastically deformed metal permitted detection of the weld plane, no evidence of a weld line could be found by light microscopy. Under these conditions the weld strength should approach parent metal strength. As has already been noted, these welds were as strong as the parent metal in both tensile and stress-rupture tests. A microhardness traverse revealed a modest decrease in microhardness of the weldment after heat-treatment from about 456 to 420 DPH. A slight variation in microhardness was found within the heat treated weldment (fig. 3(b)). Close to the weld line (not detectable), the microhardness averaged 402 DPH and the parent metal averaged 420 DPH. Fracture profiles of stress-rupture specimens tested at 760^o and 980^o C illustrate the intergranular nature of the fractures (fig. 4).

¹
Joint efficiency = $\frac{\text{Weld strength}}{\text{Parent metal strength}} \times 100.$

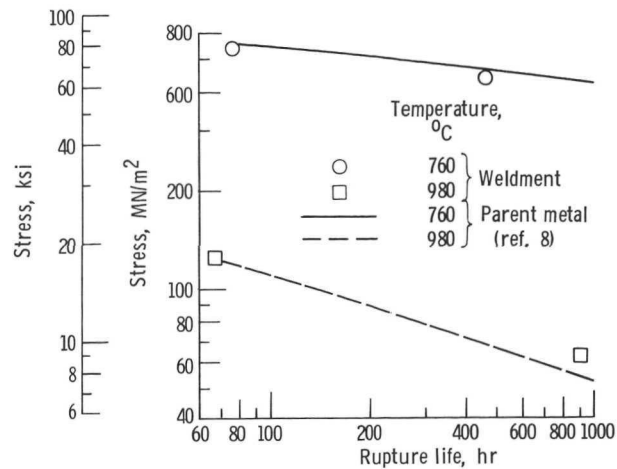
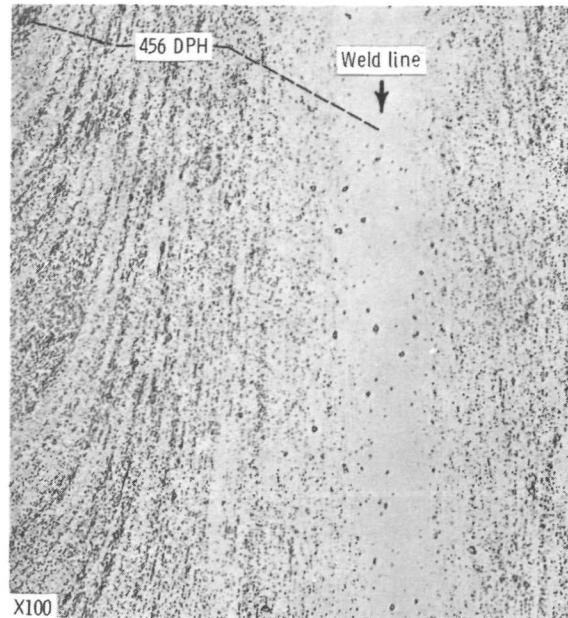


Figure 2. - Stress-rupture strength of friction welds in 12.7-millimeter (1/2-in.) diameter Udimet 700 bar at 760⁰ and 980⁰ C. Both weldments and parent metal were given the four-step Udimet 700 heat treatment before stress-rupture testing.

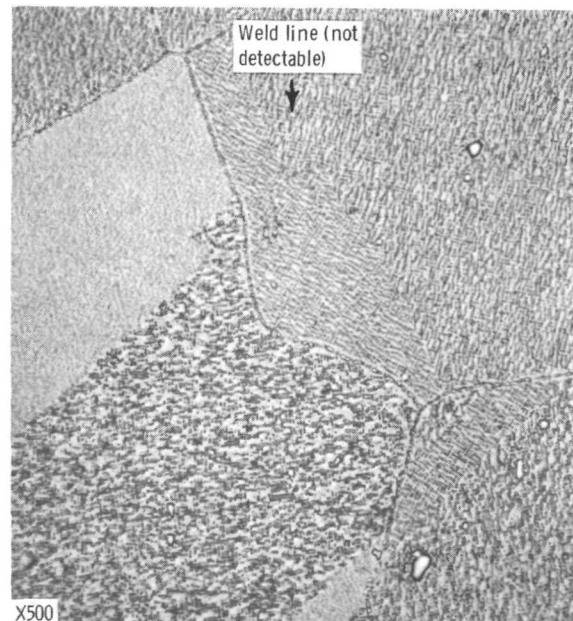
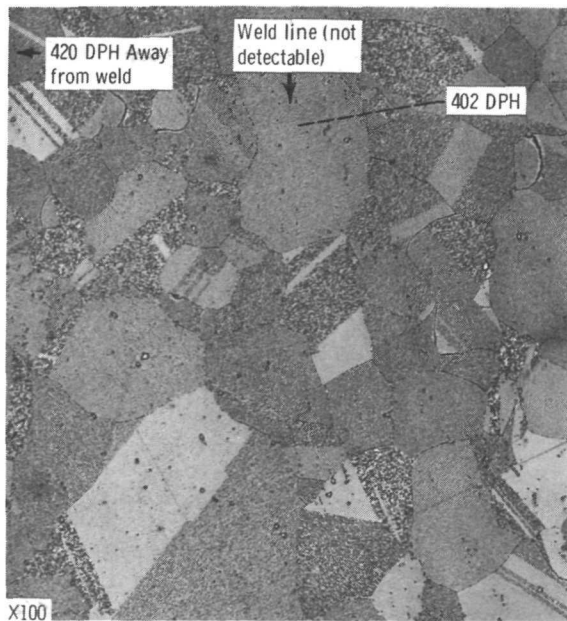
TABLE III. - STRESS-RUPTURE PROPERTIES OF FRICTION WELDS

Specimen number	Test temperature, °C	Stress		Life, hr	Elonga- tion, percent	Reduction in area, percent	Fracture location
		MN/m ²	ksi				
Udimet 700/Udimet 700							
7	760	537	78.0	76.3	10	10	Parent metal
10	760	440	64.0	460	(a)	8	Near weld
8	980	124	18.0	67.2	3	2	Near weld
11	980	62	9.0	904	(a)	3	Near weld
TD-Ni/TD-Ni							
2N	1090	24	3.5	0.06	(a)	(a)	Square edge
3N	1090	14	2.0	.25	(a)	(a)	At weld
5N	1090	9	1.3	11.4	(a)	(a)	At weld
Udimet 700/TD-Ni							
4-UN	930	55	8.0	0.02	---	(a)	Square edge
5-UN	930	28	4.0	2.3	---	(a)	At weld

^aNo measurable value.

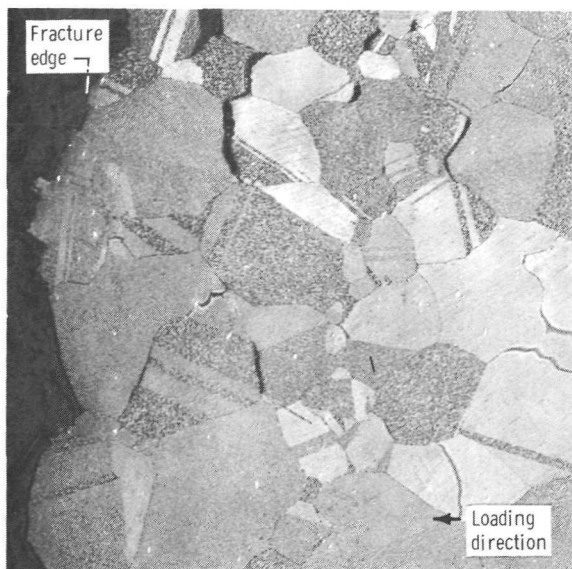


(a) As-welded.

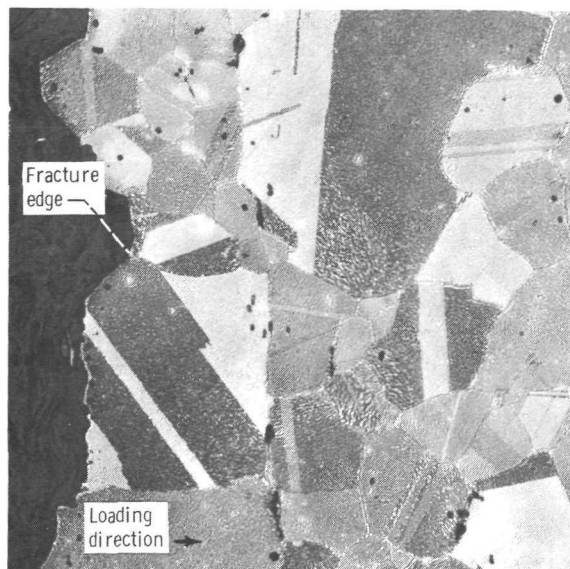


(b) Heat treated.

Figure 3. - Udimet 700 friction weld in the as-welded and (four-step) heat treated conditions. Representative microhardness (DPH) values are noted for various zones. Etchant, 92 milliliters hydrofluoric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab).



(a) Test temperature, 760° C; specimen 10.



(b) Test temperature, 980° C; specimen 11.

Figure 4. - Stress-rupture fractures of Udimet 700 friction weldments illustrating intergranular fracture near weld line (not discernable). Etchant: 92 milliliters hydrofluoric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab). X100.

TD-Nickel Weldments

Deformation pattern. - The photograph in figure 5 for TD-Ni contrasts sharply with the Udimet 700 weldment shown in figure 1. Only limited plastic deformation took place along the weld plane in the TD-Ni weld, and thus the parameters, which were selected in an arbitrary manner, did not produce a conventional friction welding flow pattern.

Mechanical properties. - In a single tensile test at 1090° C, a joint efficiency of only 30 percent was obtained (table II). In stress-rupture tests at 1090° C, the friction welds

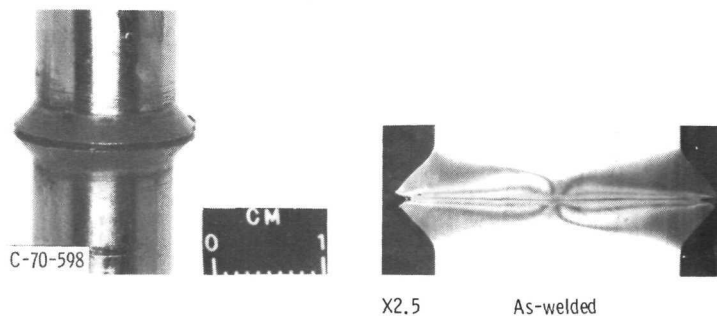


Figure 5. - Friction weld in TD-nickel showing limited plastic deformation along weld plane.

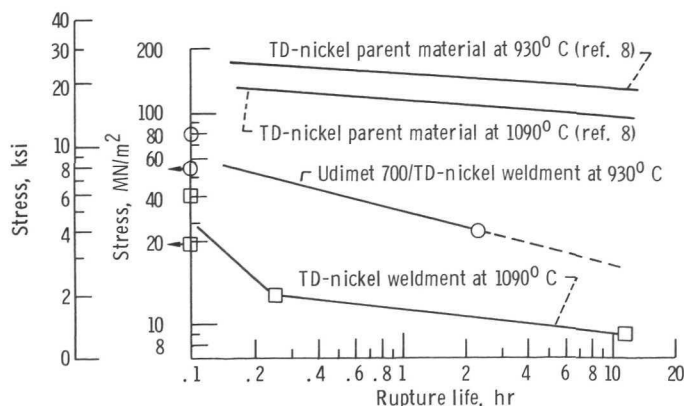
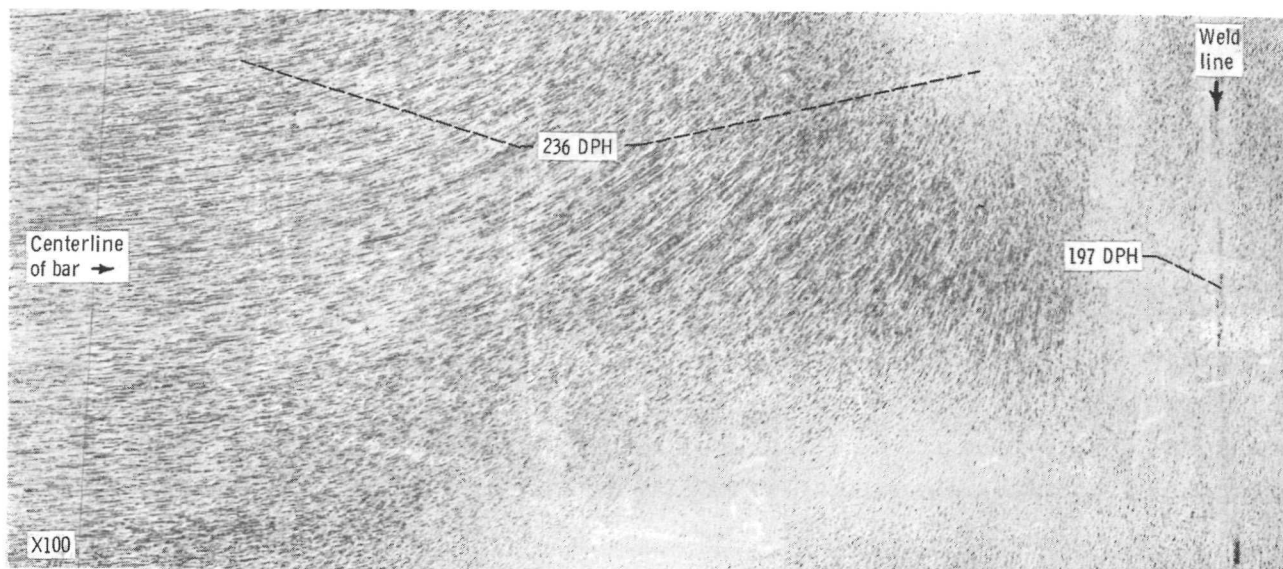


Figure 6. - Stress-rupture strength of TD-nickel and TD-nickel/Udimet 700 friction weldments.

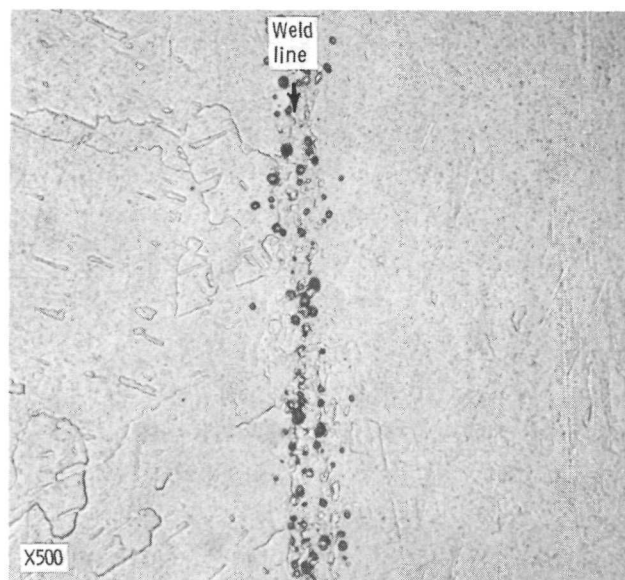
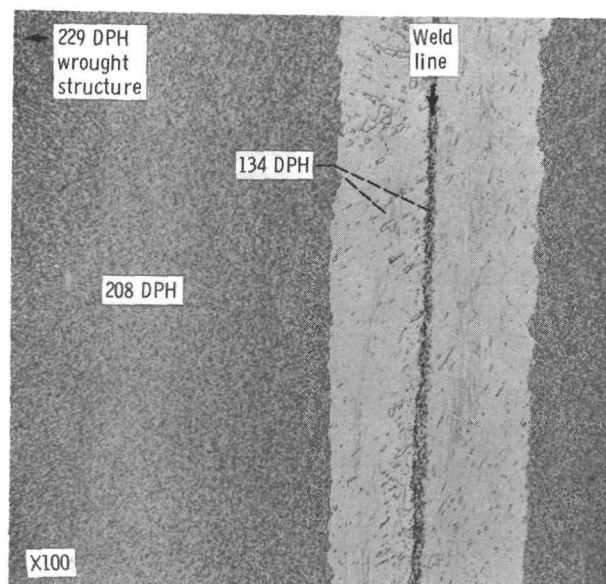
were also quite weak. The data listed in table III and plotted in figure 6 show that the weld can support only 9 percent as much load as the parent metal for a 10-hour rupture life. Earlier studies (ref. 9) had indicated that diffusion-welded butt joints in TD-Ni bar were weak in stress-rupture, but the friction welds are even weaker. This extreme weakness indicates that the original texture and thoria distribution have been destroyed at the weld joint. Even if the weld parameters were optimum for friction welds in TD-Ni, the deformation and subsequent recrystallization at the weld would be likely to result in a weak weld at elevated temperature (ref. 9).

Metallography. - In figure 7(a) grain flow lines produced during friction welding are evident in the as-welded structure. Near the weld line, however, where the material was most heavily worked, no flow lines are evident. On the basis of lower hardness near the weld line than in the wrought structure (197 against 236 DPH), some local recrystallization may have taken place during welding. Heat treatment produced a very soft (134 DPH), light-etching, recrystallized band on both sides of the weld line (fig. 7(b)). The particles at the weld line are believed to be agglomerated thoria and possibly nickel oxide. More plastic flow along the weld interface during welding, which would result in an increased quantity of squeezed-out material, might have removed these particles from within the joint.

The dark-etching, mottled structure adjacent to the recrystallized band (fig. 7(b); (magnification $\times 100$) is believed to be partially recrystallized. This assumption is based on the fact that the DPH hardness is 208 in the mottled area and 229 in the wrought structure. The wrought structure, which is characterized by long thin grains, is no longer evident within the area shown. The fracture profiles in figure 8 (specimen no. 5N, table III) show two areas of weakness. The first (on the left), which is near the centerline of the bar, is located in a region just outside of the band of white, recrystallized grains. Near the surface of the test specimen (on the right, fig. 8), frac-



(a) As-welded.



(b) Heat treated.

Figure 7. - Microstructure of as-welded and heat-treated TD-nickel friction weldments. Representative microhardness values (DPH) are indicated for various zones. Etchant: 92 milliliters hydrochloric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab).

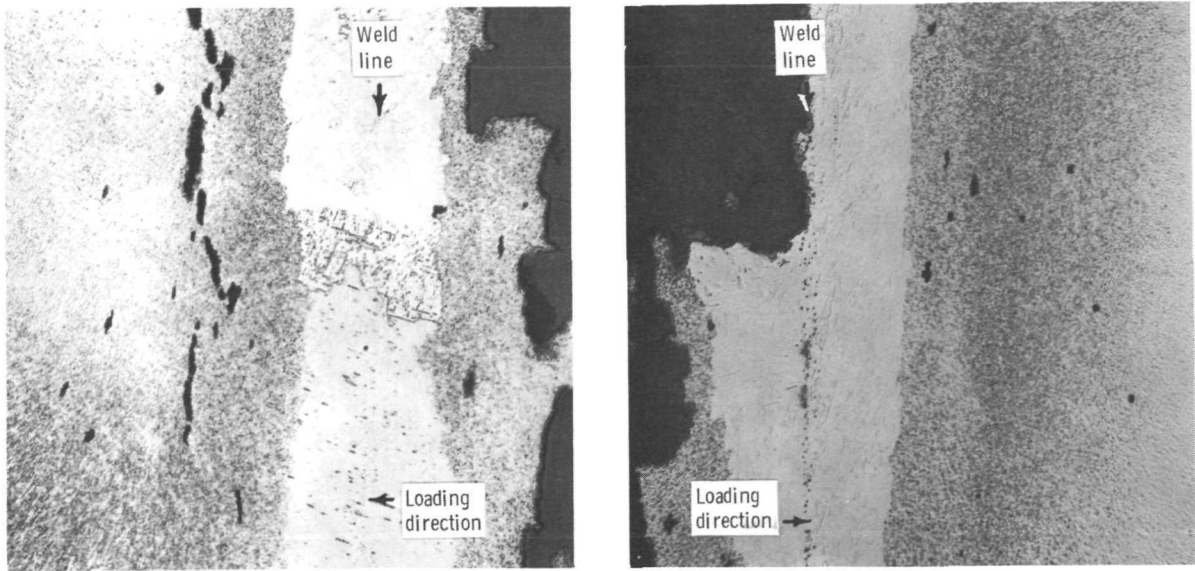


Figure 8. - Stress-rupture fractures for TD-nickel friction weldment showing weld line and parent metal fractures. Specimen 5N; test temperature, 1090° C. Etchant: 92 milliliters hydrochloric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab). X100.

ture proceeded along the weld plane where particles of thoria or possibly nickel oxide are present.

Udimet 700/TD-Nickel Weldments

Deformation pattern. - The deformation pattern for the U-700/TD-Ni dissimilar metal weld is shown in figure 9. Most of the deformation took place in the TD-Ni. The Udimet 700 bar showed very little plastic deformation at the joint. The differences in deformation behavior were probably due to differences in thermal properties and strength of the two materials. This unsymmetrical deformation pattern in friction weldments of dissimilar materials having great differences in thermal and mechanical properties has been observed by Vill' (ref. 6).

Mechanical properties. Before machining the test specimens, the dissimilar metal weldments were exposed to the same four-step heat treatment that had been used for the Udimet 700 weldments. Tensile efficiency averaging 44 percent was obtained at 930° C for duplicate tensile tests (table II). In both cases, fracture was of the square-edge, nil-ductility type located at the weld joint.

In stress-rupture tests, the weldments could support only 15 percent as much load as the parent metal for 10-hour life at 930° C (table III and fig. 6). The stress-rupture fractures were located at the weld with no measurable ductility.

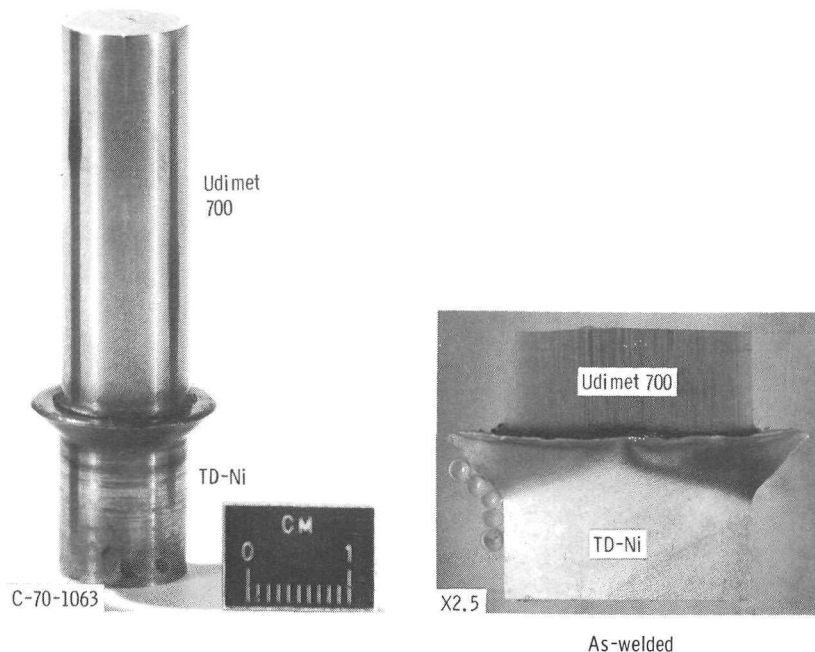
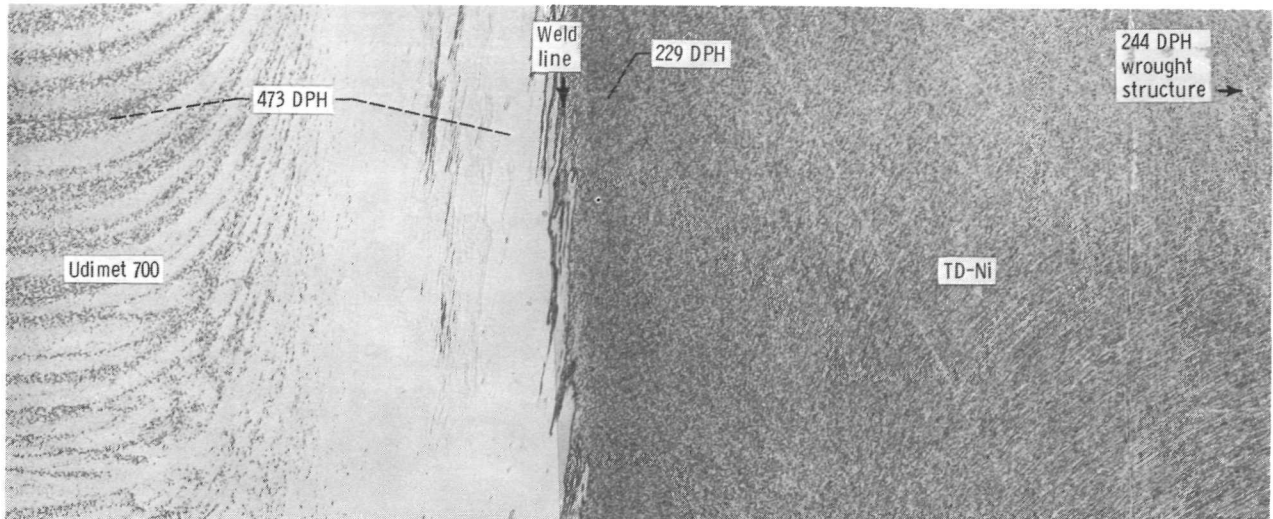
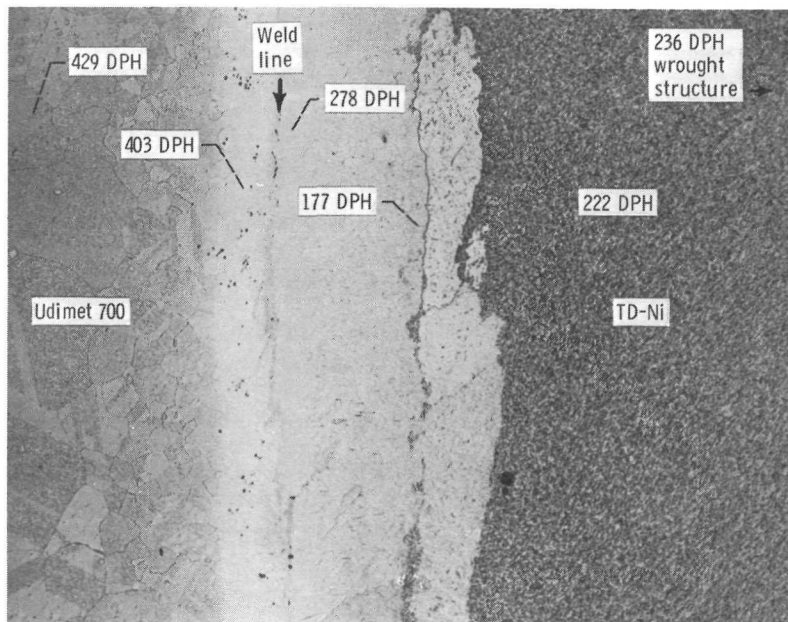


Figure 9. - Dissimilar metal friction weld between Udimet 700 and TD-nickel.

Metallography. - In the as-welded condition (fig. 10(a)) there is clear evidence of plastic deformation in the Udimet 700 bar. Although not as evident in this figure, considerable plastic flow has also taken place in the TD-Ni and complete welding has been achieved. Hardness in the Udimet 700 averages 473 DPH in the light etching area and in the wrought structure. Near the weld the TD-Ni was slightly softer than the unaffected parent metal (229 versus 244 DPH). The four-step heat treatment produced recrystallization and hardness changes in both the Udimet 700 and TD-Ni materials. The heat-treated structure in figure 10(b) shows two distinct zones in each material. On the U-700 side, there is a light-etching band (403 DPH) adjacent to the weld line. Beyond this band in the Udimet 700 parent metal is a recrystallized Udimet 700 structure which averages 429 DPH. On the TD-Ni side, a light etching region adjacent to the weld line exhibits recrystallized grains that are quite soft (177 DPH). The remaining, dark-etching TD-Ni structure shown in figure 10(b) is probably partly recrystallized as judged by the mottled structure and slightly lower hardness (222 DPH) than the wrought structure away from the weld (236 DPH). The distribution and shape of the gamma prime in the Udimet 700 and thoria in the TD-Ni were not determined since only the light microscope was used. Examination of the fracture profile in figure 11 shows that fracture took place at the weld line and within the TD-Ni parent metal. The fracture within the TD-Ni shows that the friction welding operation weakened the TD-Ni parent material especially at the junction of the white recrystallized band and the darker-etching mottled material.



(a) As-welded.



(b) Heat treated.

Figure 10. - Udimet 700/TD-nickel friction weld in the as-welded and (four-step) heat treated conditions. Representative microhardness values (DPH) are indicated for various zones. Etchant: 92 milliliters hydrochloric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab). X100.

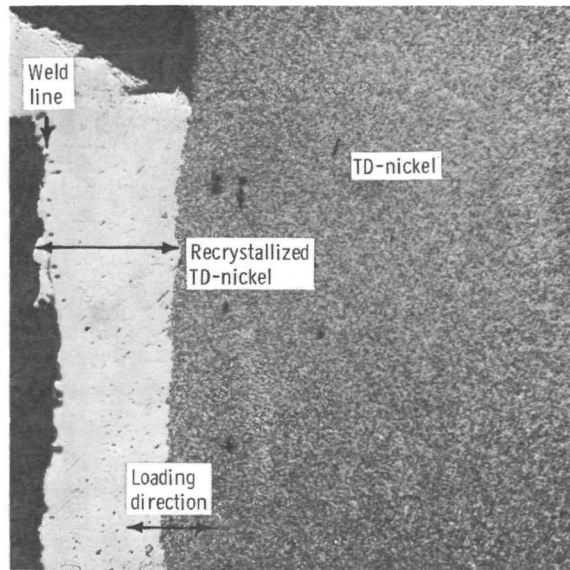


Figure 11. - Stress-rupture fractures of Udimet 700/TD-nickel friction weldment. Specimen 5N; temperature, 930° C; stress, 28 meganewtons per square meter (4 ksi); time, 2.3 hours. Fracture has taken place at the weld line and in the TD-nickel parent material. The Udimet 700 side of the joint is not shown. Etchant: 92 milliliters hydrochloric acid, 5 milliliters sulphuric acid, 3 milliliters nitric acid (swab). X100.

CONCLUDING REMARKS

Friction welds in Udimet 700 have been shown to be equal to the parent metal in tensile and stress-rupture strength at 760° and 980° C. This is highly significant because the family of PH Ni-base alloys including Udimet 700 and alloys containing high aluminum and titanium are virtually unweldable by fusion welding techniques. The problem is cracking that occurs during welding or during postheating of gas tungsten-arc or electron-beam weldments. Thus, at the present time, friction welding (a solid-state deformation welding process) should be considered where applicable for elevated temperature service applications. Stalker and Jahnke (ref. 10) state that friction welding is the most repeatable and reliable joining process that they have used for jet engine applications.

Friction welding does not appear to be applicable to TD-Ni or to Udimet 700/TD-Ni weldments. The severe localized plastic deformation inherent in the friction welding process destroys the initial textured structure and produces a recrystallized band in the TD-Ni on postheating at the weld interface. The thoria distribution at the weld plane and within recrystallized regions is probably also affected. Further development work could be done to increase plastic flow at the weld interface to insure the complete re-

removal of foreign material at the weld line. This would not solve the problem of low-strength welds in TD-Ni, however, because the inherent deformation that is produced by friction welding weakens the TD-Ni parent metal.

SUMMARY OF RESULTS

This exploratory study was designed to determine whether friction welds in Udimet 700 and thoriated nickel (TD-Ni) that match parent material properties could be produced. The microstructures of the weldments were also evaluated. Butt welds were made in 12.7-millimeter (1/2-in.) diameter bar stock in Udimet 700 and in TD-Ni. Also, dissimilar welds were made between Udimet 700 and TD-Ni. Elevated temperature properties of heat treated weldments were evaluated.

The results were as follows:

1. Stress-rupture strength and tensile strength of friction welded Udimet 700 butt joints are equivalent to those of the parent metal at 760⁰ and 980⁰ C. Postheating produced recrystallization and grain growth which eliminated all evidence of the weld line.

2. A joint efficiency¹ of only 30 percent was obtained in 1090⁰ C tensile tests of TD-Ni friction-welded butt joints. The weld was even weaker in stress-rupture tests because it could sustain only 9 percent as much load as the parent material for just a 10-hour life at 1090⁰ C. Postheating produced a weak recrystallized band at the weld joint.

3. Friction welded Udimet 700/TD-Ni butt joints had 44 percent joint efficiency (based on the weaker TD-Ni material) in 930⁰ C tensile tests. The welds were even lower in strength when tested in stress-rupture. The friction weld could sustain only 15 percent as much stress as the weaker TD-Ni material for just a 10-hour life at 930⁰ C. Postheating produced recrystallization in both parent materials.

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National Aeronautics and Space Administration,
Cleveland, Ohio, August 18, 1971,
114-03.

¹
Joint efficiency = $\frac{\text{Weld strength}}{\text{Parent material strength}} \times 100.$

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